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Final Report

NONLINEAR GRAVITY WAVE TRANSPORT AND ITS ROLE IN THE GENERAL CIRCULATION OF THE ATMOSPHERE

Prepared by
Timothy J. Dunkerton

Prepared for
Air Force Office of Scientific Research
Bolling AFB
Washington, DC

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Gravity waves play a significant role in the transport of momentum, heat, and constituents in the terrestrial atmosphere. Due to mean-flow shear, the gravity wave critical layer is a locus of isentropic overturning, secondary convective instability, turbulence, and mean flow acceleration. These processes were simulated numerically in a two-dimensional model, and a convective saturation hypothesis for breaking gravity waves was confirmed. The role of parameterized wave transport in the quasi-biennial oscillation, and effects of angular momentum advection by the mean meridional circulation, were also addressed.

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1. INTRODUCTION

Gravity waves play a significant role in the earth's atmosphere, acting to redistribute momentum, heat, and constituents in the vertical. Their ability to transport momentum over many scale heights provides an important kind of vertical coupling that strongly regulates the flow at upper levels of the mesosphere and in the lower stratosphere above tropospheric jet streams. In extratropical latitudes the retarding force associated with gravity wave breakdown closes off seasonal jets and maintains a large departure from radiative equilibrium, enhancing meridional transport indirectly through an induced secondary circulation. In the tropics, gravity wave transport (and that associated with equatorially-trapped modes) is important at all altitudes from the upper troposphere to ionosphere, affecting quasi-biennial, stratopause semiannual, and mesopause semiannual oscillations, as well as the climatological time-mean flow. Strong interactions exist between gravity waves, tides and large-scale planetary waves on a day-to-day basis.

To better understand the transport associated with gravity waves and its effect on the general circulation, a two-pronged approach is necessary. Direct simulation of all the relevant scales is impossible in current models; in fact, GCMs are just beginning to simulate the longest inertia-gravity waves and their interaction with planetary-scale flows. Since the dominant transport is probably associated with higher frequencies and smaller horizontal scales (Fritts, 1984), it is necessary, on the one hand, to study this kind of motion directly through dedicated gravity wave models, and (on the other hand) to devise parameterization schemes for gravity wave transport in large-scale general circulation models. Theoretical studies are a stimulus for both aspects of the problem.

The purpose of research supported by the Air Force Office of Scientific Research under Contract F49620-89-C-0051 has been to investigate processes governing the excitation, propagation, quasi-linear and nonlinear interaction, saturation, breakdown, and transport parameterization for gravity waves of all horizontal scales and frequencies relevant to the terrestrial atmosphere. We focus therefore not on atmospheric modeling *per se* but on modeling issues specifically associated the gravitational class of motion. This is a very large problem; our work as summarized in the following pages touches on several specific aspects currently of interest.

2. OBJECTIVES OF THE RESEARCH EFFORT

a. Numerical simulation of gravity wave critical layer

Momentum deposition due to gravity wave breakdown occurs in one of two ways: through exponential growth and saturation due to ambient density decrease with height in a compressible atmosphere, and through critical layer absorption. In atmospheric regions where gravity wave-induced accelerations are important, these effects act in tandem; for example, in the upper mesosphere where density is low and mean flows reverse sign entering the thermosphere, and in the lower stratosphere where the westerly jet streams of the troposphere are replaced by regions of weak or easterly mean flow. In both cases the effect of mean shear, with *in situ* critical layer, is important. We have therefore devoted considerable effort to understand the geophysically relevant aspects of gravity wave critical layer interactions. Specifically it is the unstable breakdown and absorption of incident gravity waves, rather than their hypothetical nonlinear reflection or critical layer transmission, that is most important. This fact is usually obscured in mathematical discussions of gravity wave critical layers, but is well-known to all who have actually modeled the critical layer, either numerically or in the laboratory.

In the present study, the major focus is on numerical simulation of gravity wave critical layers and associated processes such as secondary instability and saturation. (The author's colleague, Dr. Donald P. Delisi, is leading a major laboratory study of these interactions; these results will not form part of this report.) One key aspect of the problem is that for very high Reynolds number characteristic of free atmosphere flow, secondary instabilities within an unstable gravity wave generally develop most rapidly at horizontal scales much smaller than the primary wave. For numerical modeling, high resolution is required. Even in two dimensions, the computational requirements are formidable, although during the last few years the required resolution has finally become practical. Computational resources remain inadequate for comprehensive analysis of three-dimensional instabilities. Theory indicates that actual instabilities will either be three-dimensional to begin with, or soon become such as a result of the turbulent energy cascade. As shown in this report, the two-dimensional problem remains complex and poorly understood (there is no consensus on dominant instabilities) although significant progress in this area has been made recently. The primary

objective of the numerical modeling described here has been to study as exhaustively as possible the two-dimensional instabilities and their effects on the larger scale, while at the same time developing three-dimensional models for future investigation. There are good reasons to expect that some of the major results obtained from two-dimensional models carry over to three-dimensional flow; in particular, the existence of saturation and resultant mean flow acceleration.

b. Normal modes of secondary instability

Amplitude of gravity wave displacement increases approaching the critical layer (where phase speed equals the mean flow component parallel to the horizontal wavevector). As amplitude increases, isentropic surfaces steepen and overturn. For nearly hydrostatic waves, static instability is expected to develop rapidly compared to the time scale of the incident wave. This theoretical prediction, based on a parallel flow approximation, is at the heart of a convective saturation hypothesis (Lindzen, 1981; Dunkerton, 1982). Simulation of static instability has been difficult, however, due to resolution requirements.

Static instability is one of several possible mechanisms of 'secondary' instability, by which is meant the nonlinear instability of a nonparallel flow distorted by a large-amplitude incident 'primary' wave. Secondary instability may assume the form of vertically-oriented convection, Kelvin-Helmholtz instability, vortical modes, slantwise convection, and parametric subharmonic instability. PSI is somewhat different than the others in that horizontal and temporal scales comparable to the primary wave are involved (Dunkerton, 1987). The various forms of instability were reviewed by Dunkerton (1989a) but most of these are still being actively investigated. Our objective has been to study the two-dimensional forms of secondary instability as a prelude to modeling in three dimensions.

c. Critical layer equilibration and saturation

A central objective has been to test theoretical predictions of gravity wave equilibration or 'saturation' of an incident wave approaching the critical layer. Prior to this study, only four other investigations had any bearing on this problem, and none proved capable of testing the 'saturation hypothesis' which states that primary wave amplitude is maintained

at precisely the amount that renders isentropic surfaces vertical at the locus of maximum instability. Any overturning, it is thought, should be quickly neutralized by convection. (1) High-resolution numerical experiments by Winters and d'Asaro (1989) simulated the breakdown and dissipation of the primary wave in a vertically periodic initial-value model. Because boundary forcing effectively decayed to zero, equilibration could not be obtained. (2) Numerical modeling of breaking gravity waves in a deep compressible atmosphere (w/o shear) by Walterscheid and Schubert (1991) successfully resolved the initial convective instability, but simulations were terminated soon thereafter due to time-stepping requirements. (3) Laboratory simulation of the critical layer by Koop and McGee (1986) suggested secondary instability (convective or Kelvin-Helmholtz) but their method for maintaining constant mean flow was unfavorable to a detailed study of this phenomenon. (4) Another laboratory study by Delisi and Dunkerton (1989) clearly showed the development of secondary instability (most likely Kelvin-Helmholtz) and resulting mean flow accelerations. Equilibration was achieved, although probably an artifact of tank geometry (incident wave amplitude was altered in any case). In summary, none of these studies squarely addressed the saturation hypothesis.

d. Instability of convectively stable waves

Although the convective saturation hypothesis provides an important constraint on realizable wave amplitude, other mechanisms of instability are important, to varying degrees. It is important to note that all of these are expected to precede convective instability and thereby may also play a role in 'saturation.' (1) Gravity waves in strong mean shear should break down via Kelvin-Helmholtz instability; likewise for inertia-gravity waves with intrinsic frequency near the Coriolis frequency (Dunkerton, 1984; Fritts and Rastogi, 1985). (2) Nonhydrostatic waves may experience slantwise convective breakdown (Hines, 1988). (3) Waves of small to moderate amplitude can interact with other spectral components leading to parametric subharmonic instability (Dunkerton, 1987). (4) Vortical motions are expected to grow rapidly as incident wave amplitude approaches the convectively unstable state (Dong and Yeh, 1989).

Some of these mechanisms are amenable to 2D investigation, others require that the

transverse coordinate also be represented. (Incidentally, convective instability itself may occur most rapidly in the transverse plane, as discussed below.) Our list of objectives includes the numerical simulation of these alternative instabilities, requiring us, on the one hand, to vary mean flow configurations in the 2D model, and (on the other hand) to explore the feasibility of low-order 3D simulation of a few instability types (e.g. vortical modes, PSI).

e. Momentum transport in the quasi-biennial oscillation

The quasi-biennial oscillation or 'QBO' dominates the tropical lower stratosphere; it was elucidated by Lindzen and Holton (1968) and Holton and Lindzen (1972) as being due to the vertical transport of momentum by equatorially trapped Kelvin and Rossby-gravity waves, together with an undetermined contribution from smaller-scale gravity and inertia-gravity waves. Lateral transport of momentum by midlatitude Rossby waves is also important, particularly in the fringes of the QBO and at upper levels (Andrews and McIntyre, 1976; Dunkerton, 1985). In this context we are mainly interested in understanding the role of vertically-propagating gravity and inertia-gravity waves near the equator. Although Holton and Lindzen (1972) ignored the gravity wave component in their simple model of the QBO, it is evident from earlier considerations advanced by Lindzen and Holton (1968) that waves of any phase speed lying within the range of QBO wind speeds, regardless of horizontal scale, should assist the descent of QBO shear zones. It remains to be determined whether such waves are actually necessary, and if so, what their relative contribution to the QBO momentum balance is. Recent observations of convectively-generated gravity waves over Panama by Pfister *et al* (1992) support our belief that these waves make a substantial contribution to QBO accelerations. Taking into account upwelling by the Brewer-Dobson circulation, wave fluxes apparently must exceed climatological estimates derived from observed Kelvin and Rossby-gravity waves. A two-dimensional model was used to assess the required magnitude of vertical wave transports and the effect of induced mean meridional circulations.

f. Convective excitation of equatorial waves

In new objective of our research in the last two years has been to study the dynamics of moist processes in the tropical troposphere as they affect the excitation of vertically-propagating planetary, synoptic, and meso-scale waves. Examples of these waves include the tropical intraseasonal oscillation, planetary Kelvin waves, synoptic-scale Rossby-gravity and 'easterly' waves, and gravity waves excited by tropical cloud clusters.

3. ACCOMPLISHMENTS OF THE RESEARCH EFFORT

a. High-resolution simulations of gw critical layer

A major objective was to extend low-resolution simulations of the gravity wave critical layer (Dunkerton and Fritts, 1984) to much higher horizontal resolution in order to explicitly resolve secondary instabilities within the wave field. For this purpose, two numerical models were employed, one hydrostatic and the other nonhydrostatic. The nonhydrostatic model was described in Dunkerton (1987). Both models used identical wave parameters and domain size; horizontal and vertical resolutions were also comparable. A brief description of the hydrostatic model is now given.

This model began with hydrostatic equations of motion in log-pressure coordinates, i.e.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} + \frac{\partial \phi}{\partial x} = X \tag{3.1}$$

$$\frac{\partial \phi_z}{\partial t} + u\frac{\partial \phi_z}{\partial x} + w\left(N^2 + \frac{\partial \phi_z}{\partial z}\right) = Q \tag{3.2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} - \frac{w}{H} = 0 \tag{3.3}$$

where u and ϕ are zonal velocity and geopotential, respectively; w is vertical velocity (in log-pressure coordinates: see Holton, 1975), z is log-pressure height, and H is the density scale height. Equations were divided into zonal mean and perturbation, to be solved separately. For simulations reported here, the mean flow was held constant in time; the effect of mean flow acceleration is examined in the Appendix of Dunkerton and Robins (1992a). The entire flow was assumed two-dimensional, so that meridional velocity v and any y-variations of the flow were ignored, as was rotation ($f \equiv 0$). This left u (zonal wind) and ϕ_z ('temperature') as dependent variables of the model. Equations for u and ϕ_z were stepped forward in time using a second-order Adams-Bashforth method.

The next step was to solve for ϕ and w, accomplished by vertical integration using Simpson's rule. The integration, and evaluation of horizontal derivatives, was done in zonal wavenumber space using a fast Fourier transform between physical and spectral space. To avoid aliasing, the top one-third of zonal wavenumber spectrum was set equal to zero at each time step. A nearly-monochromatic primary wave was excited at the lower boundary by specifying w there. Profile of vertical velocity was obtained by integrating the continuity

equation to the upper boundary, where the Klemp and Durran (1983) radiation condition was imposed, giving ϕ at that point. The geopotential profile was then obtained by downward integration of ϕ_z. To avoid numerical noise at the lower boundary, nonlinear terms were artificially weighted by a sine ramp function in the lowest one-tenth of the model domain.

Various model resolutions were used. For simulations reported here, 201-401 vertical grid points gave nearly identical results, allowing the lower resolution (201) to be used for most of the nonlinear runs. Horizontal resolution included 256 zonal harmonics. However, this relatively high resolution was necessary only to represent secondary instabilities. It was acceptable to force the primary wave at lower resolution (128 harmonics) until instabilities first became visible in the spectrum (typically, about 20 orders of magnitude below the primary wave). At that point, we zero-filled the zonal wavenumber spectrum between harmonics 129-256, giving a complete spectrum of waves 1-256 for use as an initial condition in 256-harmonic runs. In retrospect, this procedure would have been an economic necessity. Fortunately, it was completely adequate for the simulations reported here.

Terms on the rhs of (2.1)-(2.2) represent dissipation in the form of scale-dependent diffusive damping (described later); they were set to zero in inviscid simulations.

b. Radiating and nonradiating instability modes

Results of hydrostatic and nonhydrostatic integrations were discussed by Dunkerton and Robins (1992a) and are summarized briefly here. Evolution of the incident wave approaching the critical layer was similar to that of Dunkerton and Fritts (1984) until isentropic surfaces overturned by a finite amount; thereafter, secondary instabilities broke out. These were of two types: nonradiating convective instability, and a new form of 'radiating' instability.

The mean Richardson number was large in these simulations. For a nonrotating fluid with weak ambient shear, convective instabilities (as opposed to Kelvin-Helmholtz instabilities) were preferred and developed at a rate consistent with the unstable stratification. Fastest growth occurred for a nonradiating mode of convective instability confined mostly within the unstable region. In an inviscid fluid there was no preferred finite horizontal scale of instability; model calculations indicated most rapid growth at the smallest resolved scales. A preferred scale was obtained with scale-dependent damping, which could also be used to

eliminate this mode; such damping was artificial in the parameter range of interest.

Radiating modes of instability were also found which have not, to our knowledge, been documented previously. The most unstable radiating mode had a three-lobed structure, with maximum amplitude in the unstable region and slightly smaller amplitude in the stable region immediately below. Although growth of this mode was somewhat smaller than the nonradiating mode, it was considered important for two reasons. First, the zonal scale was finite and relatively close to the primary wave, so this mode could, for a time, exceed the amplitude of the nonradiating mode even within the region of overturning. Second, of the two modes the radiating mode was the only one having significant amplitude outside the unstable region. Therefore, it may be important in momentum transport and constituent mixing. The significance of this result is that, until now, it was thought that if convective instability is preferred, turbulence would be confined largely to the overturned region of the wave field, and if this instability prevents any significant supersaturation, the effective diffusivity of the mean state would be weak (Fritts and Dunkerton, 1985; Coy and Fritts, 1987). Direct simulation indicated however, that supersaturation is likely initially, and radiating instabilities appear outside the region of overturning.

Theoretical analysis using a parallel-flow approximation revealed other radiating instabilities, in addition to nonradiating convection and three-lobed radiating instability, that appear as "ducted" modes above and below the unstable region. They have not been discussed here as growth rates are weaker and, in any case, further investigation of their mode trajectories is necessary.

It is interesting to speculate what would happen if the third dimension could be included in the simulations. It seems likely that the radiating mode of instability will occur in the two-dimensional plane already represented by the model, as the three-lobed structure of this mode is consistent with thermodynamic balance by virtue of alternating signs of ambient zonal velocity in this plane (cf. Section 4b). If so, the two-dimensional model has described, at least, the *initial* evolution to three-dimensional turbulence. For nonradiating convection, on the other hand, there is no reason why instability could not occur in any plane; the transverse plane might be preferred (e.g., Klaassen and Peltier, 1985).

c. Evidence of saturation in gw critical layer

In their second paper of the series, Dunkerton and Robins (1992b) described the asymptotic behavior of the critical layer.

Initial evolution of the primary wave up to the point of overturning (around 17000 sec) was virtually identical in hydrostatic and nonhydrostatic simulations. The radiating mode of secondary instability was also similar (not shown). As instabilities grew and became chaotic, results of the two models began to diverge. For various reasons the hydrostatic simulations could not be trusted beyond this point (see below); we therefore limit attention to nonhydrostatic results.

By 30000 sec, the vertical velocity spectrum had equilibrated to its final shape. The most important observation is that while finestructure in the turbulent critical layer changed continually with time, the low-pass field remained essentially the same throughout the remainder of simulation (from 30000 to 50000+ sec). Low-pass filtered potential temperature contours overturned from time to time but did not remain overturned; on average they were neutral to convection and hence suggest a 'saturation' of primary wave. In fact, the low-wavenumber flow did not differ much from low-resolution simulations with convective adjustment (see Dunkerton and Fritts, 1984). Our simulations therefore provided the first direct confirmation of the saturation hypothesis.

There was some evidence of critical layer 'transmission' in low- and high-wavenumber components although the effect was rather small. Dunkerton (1987) observed a small amount of transmission due to resonant interaction. Here it is more likely that transmitted components were generated in the turbulent critical layer and were therefore mostly nonresonant.

Comparing these results with hydrostatic simulations, the hydrostatic approximation was valid for the primary wave and (qualitatively, at least) secondary instability also. However, there was an essential difference between the two models after overturning and development of critical-layer turbulence. This could be seen in the amount of *downward-propagating secondary wave activity* below the critical layer.

The nonhydrostatic model required that intrinsic frequency not exceed BV frequency for vertical propagation. Consequently, downward propagation at high zonal wavenumber was prevented. Such disturbances were instead evanescent.

The hydrostatic model had no such requirement. As a result, the convection continuum not only dominated the critical layer but launched narrow waves propagating down to the model lower boundary! In this sense the critical layer simulation with hydrostatic code was not only unrealistic but numerically ill-behaved. (We caution against the use of hydrostatic models in this context unless care is taken to prevent spurious wave propagation.)

Similar experiments were done with mean-flow modification due to gravity-wave momentum flux convergence (as described in the Appendix of Dunkerton and Robins, 1992a).

d. Resonant and nonresonant interactions

Dunkerton (1987) observed that under certain circumstances it was possible for incident waves to decay by parametric subharmonic instability and thereby excite other waves, both upward and downward propagating. Examples were found in which the upward component was transmitted to higher levels (above the initial critical layer) – in fact, to the critical layer of the new wave.

It was also noted that convective instability did not prevent these weakly nonlinear interactions, although it preceded them in time. (It will be interesting to determine whether both strongly- and weakly-nonlinear instabilities can coexist in a numerical simulation. This matter remains to be addressed.) For the moment, we conclude that convective saturation alone does not prevent other, weaker forms of nonlinear interaction and therefore supports the earlier conclusions of Dunkerton (1987) in which the saturation hypothesis was assumed *a priori*.

e. Angular momentum balance of QBO

Using parameterized forms of equatorial wavedriving in a two-dimensional (latitude-height) model, Dunkerton (1991) discussed the momentum balance of the QBO, including effects of (1) wave-induced mean meridional circulations and (2) the background (climatological) Brewer-Dobson circulation. This paper also extended the theory of asymmetric Hadley circulation developed by Dunkerton (1989b) to include a mesospheric friction layer, more realistic representation of midlatitude Rossby wave drag, and their effect on the stratopause semiannual oscillation.

Our main conclusion concerning the QBO is that observed fluxes due to Kelvin and Rossby-gravity waves are inadequate (by themselves) to drive the QBO when vertical advection of shear by the mean meridional circulation is taken into account. Either our model miscalculated this circulation in the equatorial lower stratosphere – which is possible, since the radiative balance is very delicate – or, in fact, other components of the wave spectrum contribute to the observed accelerations (Pfister, *et al*, 1992).

f. Conditional heating in tropical waves

Convective excitation of equatorial waves is fundamentally important on many space and time scales in the tropical troposphere. Our recent work in this area began by examining the excitation of intraseasonal oscillations first observed by Madden and Julian (1971, 1972). As shown by Parker (1973) these oscillations include a low-frequency Kelvin wave radiating across the tropopause which, according to calculations of Dunkerton (1991), may contribute to the uniform descent of QBO westerly shear.

Mechanistic models of CISK and evaporation-wind feedback were generalized by us to include conditional heating, i.e. positive-only heating within cloud clusters, and the resulting unstable circulations were determined. Our main result is that scale-selection does not occur at any finite zonal scale, as in linear theory. Unlike linear solutions, the favored unstable configuration with positive-only heating includes a single wet region with exponential tail on either side (this aspect is in accord with observations). We recently verified these analytic results with a three-dimensional beta-plane model (Crum and Dunkerton, 1992, manuscript in preparation). Improved representations of moist thermodynamics are now being considered.

4. LIST OF PUBLICATIONS ARISING FROM THIS WORK

Dunkerton, T.J., 1991: Nonlinear propagation of zonal winds in an atmosphere with Newtonian cooling and equatorial wavedriving. *J. Atmos. Sci., 48,* 236-263.

Dunkerton, T.J., and R.E. Robins, 1992: Radiating and nonradiating modes of secondary instability in a gravity wave critical layer. *J. Atmos. Sci.*, in press.

Dunkerton, T.J., and R.E. Robins, 1992: Evidence of saturation in a gravity wave critical layer. *J. Atmos. Sci.*, in press.

Dunkerton, T.J., 1992: Inertial instability of nonparallel flow on an equatorial beta-plane. *J. Atmos. Sci*, in press.

5. CONCLUSIONS AND RECOMMENDATIONS

The convective saturation hypothesis of Lindzen (1981) and Dunkerton (1982) was successfully verified in direct numerical simulation of the gravity wave critical layer (Dunkerton and Robins, 1992a,b). Monochromatic incident waves experience isentropic overturning, secondary instability (leading to turbulence confined to the critical layer), and mean flow acceleration – as predicted by the saturation hypothesis. Two avenues of further study are required before drawing general conclusions from this result.

First, the role of alternative secondary instabilities in the two-dimensional problem must be addressed. We expect Kelvin-Helmholtz instability in the critical layer prior to convective instability when initial mean shear is strong (Dunkerton, 1989a); this was observed in the laboratory by Delisi and Dunkerton (1989). We also expect long-lived incident waves to gradually succumb to parametric subharmonic instability in the stable region beneath the critical layer (Dunkerton, 1987) even when the incident wave experiences convective saturation at higher levels. Crude parameterizations of these processes were developed (Dunkerton, 1984, 1989a) but remain to be tested by direct numerical simulation.

Second, the role of three-dimensional instability needs to be explored in both rotating and nonrotating systems. For nonrotating waves, vortical modes are expected about the same time isentropic overturning begins (Dong and Yeh, 1989). For inertia-gravity waves, Kelvin-Helmholtz instability should occur long before convective instability when intrinsic frequency approaches the Coriolis frequency (Dunkerton, 1984). [In this respect the inertia-gravity wave critical layer is qualitatively different from that of nonrotating waves; implications for heat and constituent transport are also different (Fritts and Dunkerton, 1985).] Numerical simulation of 3D secondary instability is not yet possible at the required resolution, but low-order experiments appear feasible for vortical modes (D.C. Fritts, personal communication, 1992). We will continue developmental work on three-dimensional models (emphasizing the longer inertia-gravity waves and equatorially-trapped modes) to explore these processes. Meanwhile, the author will generalize parallel-flow instability calculations of Dunkerton and Robins (1992a) to three-dimensional flow – as recently done by Klostermeyer (1992) for parametric subharmonic instability – to compare the efficiency of 2D and 3D instability mechanisms.

Beyond the problem of simulating gravity waves in dedicated models is their parameterization in GCMs and role in the general circulation. More realistic simulation of the QBO must be done to understand the effect of gravity waves on momentum transport in this oscillation. Observations don't yet specify the gw spectrum as a function of zonal wavenumber, but modeling allows many choices to be attempted to see which gives the most realistic result. We began this type of study in Dunkerton (1991) but much remains to be done. Similar issues arise in the stratopause semiannual oscillation.

Finally, the role of moisture in excitation of tropical waves and instabilities (including effects of mean flow shear leading to inertial and divergent barotropic instability) is far from being understood. Part of the problem concerns our understand of dynamics *per se*; the other concerns the proper representation of moist thermodynamics and tropical convection – insofar as these must be parameterized as unresolved, sub-grid scale processes. (We cannot yet resolve tropical cloud clusters in global models.) Solution of these difficulties is essential to modeling tropical wave excitation, propagation, and troposphere-stratosphere coupling via momentum transport. In a broader context, the hydrologic cycle and global climate are significantly influenced by tropical motions. Therefore, despite the seemingly disconnected nature of tropical mean-flow phenomena at different levels, wave transport that couples these phenomena together also reminds us that all are part of a larger atmosphere-ocean climate system.

6. PERSONNEL ASSOCIATED WITH THE RESEARCH

Dr. Robert E. Robins of Northwest Research Associates assisted in programming hydrostatic and nonhydrostatic models of the gravity wave critical layer. Dr. Francis X. Crum, a postdoctoral associate at NWRA supported by Dr. Dunkerton's research funds, participated in the study of moist tropical waves and instabilities. In addition to their input, the author has benefited from numerous discussions with Drs. David C. Fritts (gravity wave observations), Donald P. Delisi (laboratory simulations of gravity wave critical layers), Donal O'Sullivan (inertial instability and QBO/planetary wave interactions), Peter H. Haynes (Hadley circulations), Harry Hendon (Rossby-gravity waves) and David Battisti (tropical dynamics).

7. PRESENTATIONS

The author has made several invited oral and poster presentations at national and international meetings in the last three years, including those of the American Meteorological Society (Waves and Stability, Tropical Meteorology, and Middle Atmosphere), American Geophysical Union, and IAMAP/IUGG in Vienna.

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